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(54) Title: AM COMPATIBLE DIGITAL WAVEFORM DEMODULATION USING A DUAL FFT
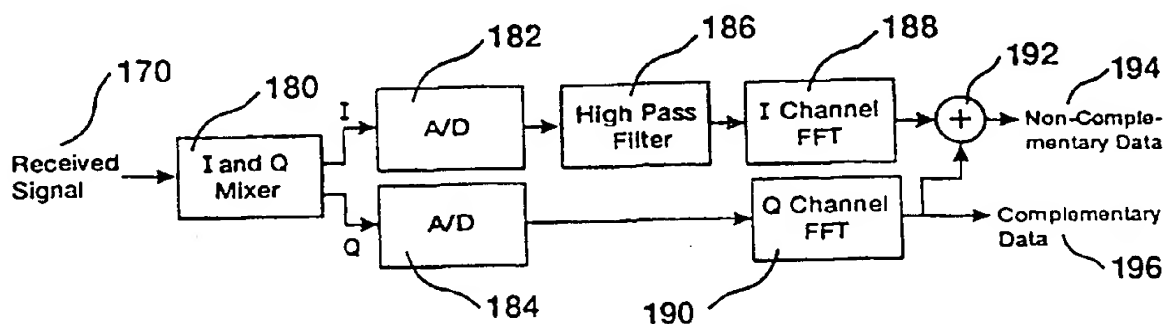
(57) Abstract

The invention provides a method and apparatus for demodulating a composite AM DAB waveform which contains digitally modulated carriers and which employ a mixer (180) for converting a received signal (170) into two signals, the first of these signals represents an in-phase component and the second of the signals represents a quadrature component, two analog-to-digital converters (182, 184) for converting the two signals into digital signals, and two fast Fourier transform elements (188, 190) for extracting data separately from the two digital signals. Complementary digital carrier signals are recovered from the quadrature, and non-complementary digital carriers are derived from a sum of the complementary data and the output of the in-phase component FFT process. Leakage of the AM signal through a highpass filter (186) is prevented from interfering with the demodulation of the complementary carrier signal's use of separated demodulation channels.

AM COMPATIBLE DIGITAL WAVEFORM DEMODULATION USING A DUAL FFT

5

BACKGROUND OF THE INVENTION

This invention relates to waveform demodulation, and more particularly to methods of and apparatus for receiving and demodulating digitally modulated signals and analog amplitude 10 modulated signals within the same frequency channel assignment.

Broadcast and reception of digitally-encoded audio signals is expected to provide improved audio fidelity. Several approaches have been suggested. Out-of-band techniques provide broadcast of digital radio signals in a specially 15 designated frequency band. In-band techniques provide broadcast within substantially vacant slots between adjacent channels in the existing broadcast band (interstitial approach) or in under-utilized portions within the same frequency channel allocations currently used by commercial broadcasters (in-band 20 on-channel or IBOC approach). The in-band on-channel approach may be implemented without the need for additional frequency coordination and with relatively minor changes to existing transmitting equipment. It is also a requirement that any digital audio broadcasting (DAB) technique must not degrade 25 analog signal reception by conventional analog receivers.

In-band approaches to digital audio broadcasting have thus far only been proposed in the FM band (88 MHz to 108 MHz), since the bandwidth of AM channels is relatively narrow as compared to the FM band allocation. However, high fidelity 30 digital audio broadcasting in the AM band (530 kHz to 1700 kHz) would provide AM broadcasting stations with a means to compete with high-quality, portable audio sources such as cassette tapes and compact disc players. It would therefore be desirable to promote an in-band on-channel (IBOC) approach in 35 the AM broadcasting band to provide enhanced fidelity through digital signalling without affecting reception by existing analog AM receivers.

An AM compatible digital broadcast waveform which satisfies the requirement of substantial orthogonality between

a conventional analog AM signal and a digitally modulated
signal set has been developed. The waveform is described in
U.S. Patent Application Serial No. 08/206,368 filed March 7,
1994, entitled METHOD AND APPARATUS FOR AM COMPATIBLE DIGITAL
5   BROADCASTING. The waveform spectrum consists of in-phase and
quadrature components. An in-phase radio frequency (RF)
carrier is modulated by an analog audio signal and the in-phase
component of a digital signal. The quadrature-phase RF carrier
is modulated by the quadrature component of the digital signal.
10 The digital signal has an orthogonal frequency division
multiplexed (OFDM) format. The in-phase signal consists of the
conventional analog AM signal and selected digital carriers.
The in-phase digital carriers are placed outside of the
spectral region occupied by the analog AM signal. The
15 quadrature-phase carriers are situated both within and outside
the spectral region occupied by the analog AM signal (although
not at the center frequency occupied by the unmodulated analog
carrier). The quadrature digital carriers situated within the
same spectral region as the analog AM signal are called
20 complementary carriers. The above described arrangement is
further described in U.S. Patent Application Serial No.
08/368,061 filed January 3, 1995, entitled METHOD AND APPARATUS
FOR IMPROVING AM COMPATIBLE DIGITAL BROADCAST ANALOG FIDELITY.
        The context of the present invention is a need to
25 demodulate the composite waveform with minimal crosstalk. The
modulated composite waveform is produced by a modulation method
in which an analog amplitude modulated (AM) signal and a
digital signal which may be a representation of the analog
audio signal (or it may be any other digital signal) are
30 encoded together and transmitted simultaneously in the same
frequency channel. This approach places some of the digital
carriers in quadrature with the analog AM, thereby enabling the
AM DAB data to be extracted and decoded with high fidelity and
without crosstalk, assuming the receiver is capable of proper
35 signal separation.
        A receiver (which is not necessarily prior art) has
been considered which converts the signal to baseband using
conventional I and Q mixers, with the I channel signal being

passed through a digital high pass filter to separate the
digital signal from the analog signal, as hereinafter
explained, a problem has been discovered related to crosstalk
between the analog signal and the digital signal. In the

5   receiver under consideration, the analog signal interferes with
the demodulation of the complementary carriers if the
demodulation of the I and Q component samples is carried out in
a single common FFT processor. What is needed is a
demodulation technique which minimizes the undesired crosstalk

10   between the analog signal and the digital signals.

SUMMARY OF THE INVENTION

                    According to the invention, in an AM compatible
digital audio broadcasting (AM DAB) system using an orthogonal

15   frequency division multiplexed (OFDM) modulation format, a
radio frequency receiving and demodulating method and apparatus
employs dual fast Fourier transform processes on separate.
respective in-phase and quadrature-phase components of a
received OFDM digital signal, the output of the quadrature

20   channel being used to recover the complementary data, and the
resultant processed component signals being summed to recover
the non-complementary data.

                    The apparatus includes a mixer for converting a
received signal into two signals, the first of the two signals

25   representing an in-phase component and the second of the two
signals representing a quadrature component; two analog-to-
digital converters for converting the two signals into digital
signals; and two fast Fourier transform processors for
extracting data from the two signals.

30   The present invention provides better and higher
resolution data extraction than heretofore known. Moreover,
the invention can be useful in providing an in-band, on-channel
(IBOC) solution to digital audio broadcasting (DAB) in the AM
frequency band.

35   The advantages of the waveform of the present
invention are that (1) the existing analog AM broadcast
channels can be upgraded to digital without requiring a new FCC
frequency allocation, (2) the AM broadcast stations can be

upgraded to a digital broadcast format with only limited
capital expenditure, (3) the composite waveform at appropriate
digital power levels yields a coverage area that is essentially
equivalent to the existing analog AM station, (4) the existing
5   AM receivers can recover the analog portion of the composite
signal without modification, and (5) interference between the
digital signal and the analog signal is minimized.

A description of the AM DAB waveform involved is
presented in U.S. Serial No. 08/206,368, filed on March 7,
10   1994, which is herein incorporated by reference.

A further understanding of the nature and advantages
of the invention will become apparent by reference to the
remaining portions of the specification and drawings.

15   **BRIEF DESCRIPTION OF THE DRAWINGS**
The invention will be more readily apparent to those
skilled in the art by reference to the accompanying drawings
wherein:
Fig. 1 is a spectral representation of the in-phase
20   component of a composite analog AM and digital broadcasting
signal;
Fig. 2 is a spectral representation of the quadrature
component of a digital broadcasting signal;
Fig. 3 is a block diagram of a demodulator which has
25   been considered for the subject waveform;
Fig. 4 is a block diagram of a demodulator in
accordance with the present invention;
Fig. 5 is a representation of the signal-to-noise
ratio (SNR) for carriers of the receiver shown in Fig. 3; and
30   Fig. 6 is a representation of the signal-to-noise
ratio (SNR) for carriers of the receiver in Fig. 4.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS
This invention provides a method of simultaneously
35   receiving both an analog amplitude modulated signal and a
digital signal on the same channel assignment as the existing
analog AM broadcasting allocation.

      The AM DAB waveform of the present invention has been previously explained. Fig. 1 is a spectral representation of the in-phase component of a composite analog AM and digital broadcasting signal. The in-phase component contains the

5   conventional analog AM signal 100 and non-complementary digital carriers 102. The in-phase component does not have any digital carriers 102 in the spectral region occupied by the analog AM signal 100.

      Fig. 2 is a spectral representation of the quadrature

10 component of a digital broadcasting signal. The quadrature portion of the spectrum as shown in Fig. 2 contains only digital carriers 110 and 112. The digital carriers that lie outside the spectral region of the analog AM signal 100 are non-complementary signals 112, and the digital carriers that

15 lie in the same frequency region as the analog AM signal 100 are complementary signals 110.

      Fig. 3 illustrates a demodulator which was considered in connection with the waveform herein described. The demodulation technique converts the signal 140 to baseband

20 using conventional I and Q mixer 150. Mixer 150 separates the in-phase and quadrature components of the received signal. The I and Q channels are then digitized in analog-to-digital (A/D) converters 154 and 156. Following A/D converter 154, the I channel is passed through high pass filter 152 which is

25 designed to eliminate the analog AM signal. The high pass filter 152 is in the real world less than ideal, which gives rise to some of the problems overcome by the present invention. The I and Q channels are then input to a fast Fourier transform (FFT) processor 158 in order to recover and obtain the received

30 data.

      While the device revealed in Fig. 3 will demodulate the signal involved, there is room for improvement. In particular, the receiver of Fig. 3 has several problems. For example, some of the analog AM signal leaks through highpass

35 filter stopband 152 and interferes with the demodulation of the complementary carriers.

      Fig. 4 illustrates how demodulation is performed in the present invention. This new demodulation technique avoids

the problem of the demodulation technique illustrated in Fig. 3
by using two FFTs which operate separately on the I and Q
channels. The received signal 170 is converted to baseband by
conventional I and Q mixer 180. As with mixer 150, mixer 180
5   separates the in-phase and quadrature components of the
received signal. The I and Q channels are then separately sent
to A/D converters 182 and 184 where they are digitized. The I
channel is passed through high pass filter 186 which attempts
to eliminate the analog AM signal. The I and Q channels are
10   then processed separately with dual FFT processors 188 and 190.
The output from the Q channel is used to recover the
complementary carriers, and the sum of the I and Q channels is
used to recover the non-complementary carriers.

       The demodulation technique illustrated in Fig. 4
15   stops leakage of the AM signal through the highpass filter from
interfering with the demodulation of the complementary
carriers. This technique also reduces the effects of noise and
compensates for non-ideal operation of the I and Q mixer.

       The demodulation techniques illustrated in Fig. 3 and
20   Fig. 4 are implemented using common, commercially-available RF
hardware, such as mixers and general purpose Digital Signal
Processors (DSPs) with software to provide the various features
of the demodulator (e.g., FFTs).

       Fig. 5 shows the SNR for carriers when the receiver
25   shown in Fig. 3 is used. The low SNR in FFT bins +16 to +19
and -19 to -16 causes the bit error rate to increase. The
carriers in these FFT bins are near the edges of the
complementary band, and the corresponding SNR is approximately
16 dB.

30   Fig. 6 is a plot of SNR for carriers when the
demodulator illustrated in Fig 4 is used. The SNR for the
complementary carriers in Fig. 6 is approximately 33 dB. This
is a significant improvement over the SNR for the complementary
carriers for the demodulator illustrated in Fig. 3 and a lower
35   bit error rate results. With the improved demodulator of Fig.
4, the signal can be received further away from the system's
transmitter.

Although the foregoing invention has been described
in some detail by way of illustration and example, for purposes
of clarity of understanding, it will be obvious that certain
changes and modifications may be practiced within the scope of
5   the appended claims.

WHAT IS CLAIMED IS:

1.   1.   An apparatus for demodulating a composite signal, the
2. composite signal including a first carrier signal amplitude
3. modulated by an analog message signal and a second signal
4. comprising a plurality of digitally modulated carriers,
5. comprising:
6.   means for separating the second signal into a third
7. signal and a fourth signal, the third signal representing an
8. in-phase component and the fourth signal representing a
9. quadrature phase component of the composite signal;
10.   first means coupled to receive the in-phase component
11. for converting the in-phase component to an in-phase digital
12. signal;
13.   second means coupled to receive the quadrature
14. component for converting the quadrature component to a
15. quadrature digital signal;
16.   a first fast Fourier transform means for extracting
17. in-phase data from the in-phase digital signal; and
18.   a second fast Fourier transform means for extracting
19. quadrature data from the quadrature digital signal.

1.   2.   The apparatus for demodulating according to
2. claim 1, wherein the quadrature phase component comprises
3. complementary carriers and non-complementary carriers.

1.   3.   The apparatus for demodulating according to
2. claim 2, wherein the first carrier signal and the complementary
3. carriers are located in a same frequency region.

1.   4.   The apparatus for demodulating according to
2. claim 1, wherein the means for separating is a quadrature
3. mixer.

1.   5.   The apparatus for demodulating according to
2. claim 1, wherein the first means and the second means are
3. analog-to-digital converters.

1   6.   The apparatus for demodulating according to
2 claim 1, further comprising:
3   means coupled to receive the in-phase data and the
4 quadrature data, and for combining the in-phase data and the
5 quadrature data to produce a fifth digital signal, the fifth
6 digital signal being representative of non-complementary data.

1   7.   The apparatus for demodulating according to
2 claim 1, wherein the in-phase digital signal is phase coherent
3 with the first carrier signal.

1   8.   The apparatus for demodulating according to
2 claim 1, wherein the composite signal is a radio frequency (RF)
3 signal, and wherein the second signal comprising a plurality of
4 digitally modulated carriers is modulated in an orthogonal
5 frequency division multiplexed format.

1   9.   A method of demodulating a composite signal, the
2 composite signal including a first carrier signal amplitude
3 modulated by an analog message signal and a second signal
4 comprising a plurality of digitally modulated carriers, the
5 method comprising the steps of:
6   receiving the composite signal;
7   separating the composite signal into a third signal
8 and a fourth signal, the third signal representing an in-phase
9 component and the fourth signal representing a quadrature phase
10 component of the composite signal;
11   converting the in-phase component to an in-phase
12 digital signal, the in-phase digital signal being phase
13 coherent with the analog carrier;
14   converting the quadrature component to a quadrature
15 digital signal;
16   extracting in-phase data from the third signal by
17 means of a first fast Fourier transform; and
18   extracting quadrature data from the fourth signal by
19 means of a second fast Fourier transform.

1   10.   The method for demodulating a composite signal
2 according to claim 9, wherein the quadrature data modulates
3 complementary quadrature amplitude modulated carriers.

1   11.   The method for demodulating a composite signal
2 according to claim 9, further comprising:
3   combining the in-phase data and the quadrature data
4 to produce a fifth signal, the fifth signal comprising non-
5 complementary data.

1   12.   The method for demodulating a composite signal
2 according to claim 9, wherein the first fast Fourier transform
3 and the second fast Fourier transform are performed
4 substantially simultaneously.

AMENDED CLAIMS

[received by the International Bureau on 17 January 1997 (17.01.97);
original claim 9 amended; remaining claims unchanged (1 page)]

1   6.   The apparatus for demodulating according to
2 claim 1, further comprising:
3   means coupled to receive the in-phase data and the
4 quadrature data, and for combining the in-phase data and the
5 quadrature data to produce a fifth digital signal, the fifth
6 digital signal being representative of non-complementary data.

1   7.   The apparatus for demodulating according to
2 claim 1, wherein the in-phase digital signal is phase coherent
3 with the first carrier signal.

1   8.   The apparatus for demodulating according to
2 claim 1, wherein the composite signal is a radio frequency (RF)
3 signal, and wherein the second signal comprising a plurality of
4 digitally modulated carriers is modulated in an orthogonal
5 frequency division multiplexed format.

1   9.   A method of demodulating a composite signal, the
2 composite signal including a first carrier signal amplitude
3 modulated by an analog message signal and a second signal
4 comprising a plurality of digitally modulated carriers, the
5 method comprising the steps of:
6   receiving the composite signal;
7   separating the composite signal into a third signal
8 and a fourth signal, the third signal representing an in-phase
9 component and the fourth signal representing a quadrature phase
10 component of the composite signal;
11   converting the in-phase component to an in-phase
12 digital signal, the in-phase digital signal being phase
13 coherent with the first carrier signal;
14   converting the quadrature component to a quadrature
15 digital signal;
16   extracting in-phase data from the third signal by
17 means of a first fast Fourier transform; and
18   extracting quadrature data from the fourth signal by
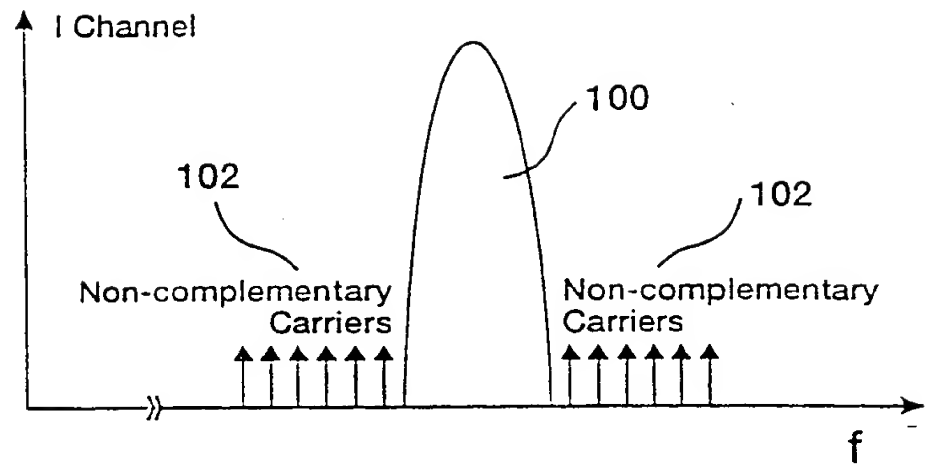19 means of a second fast Fourier transform.
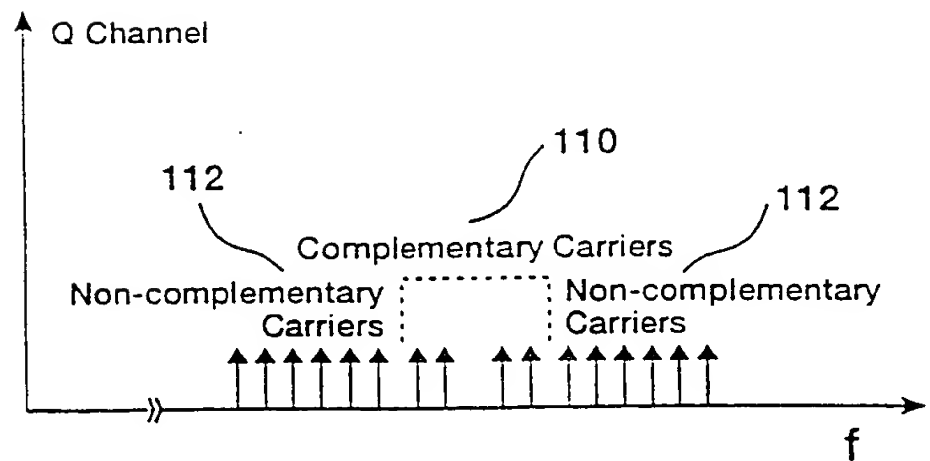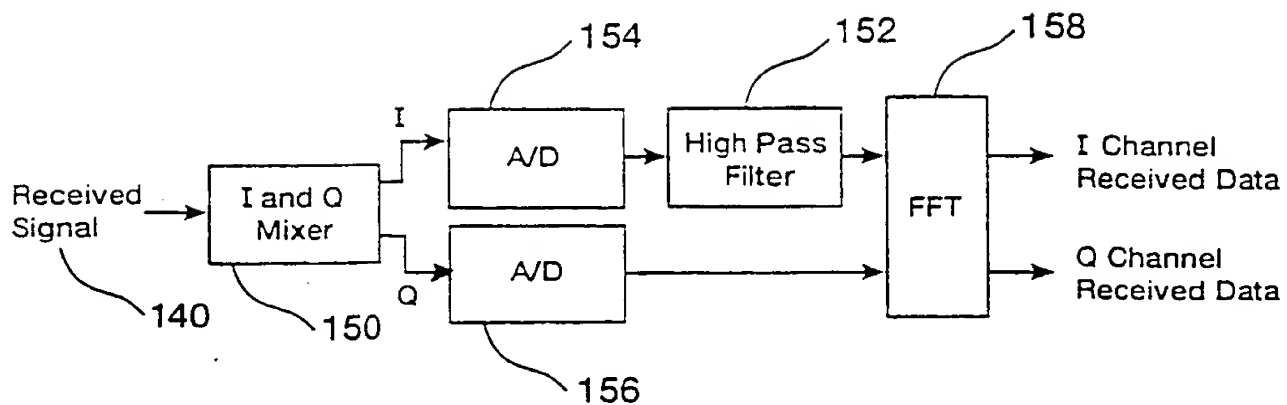
AMENDED SHEET (ARTICLE 19)

Fig. 1

Fig. 2

Fig. 3
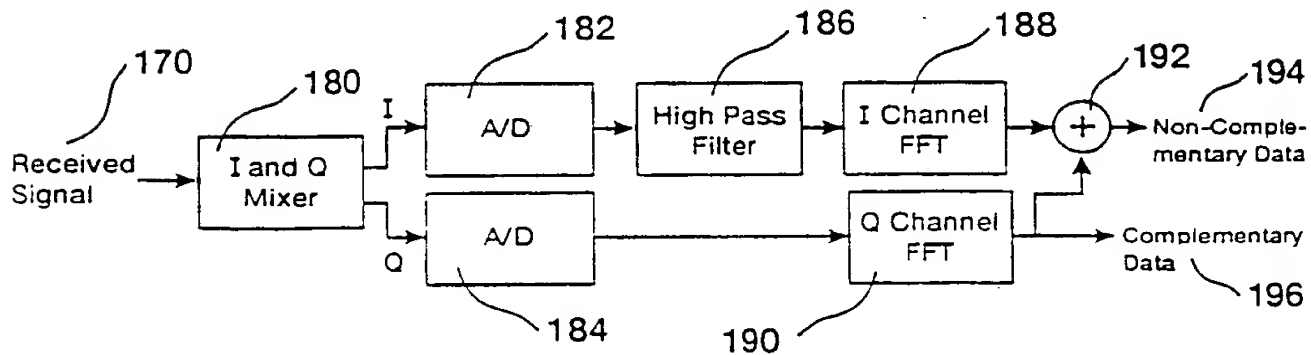
Fig. 4
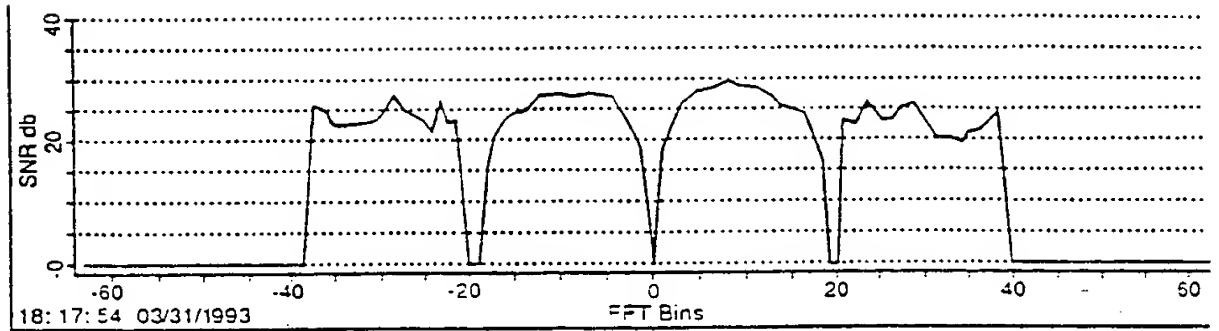
Fig. 5
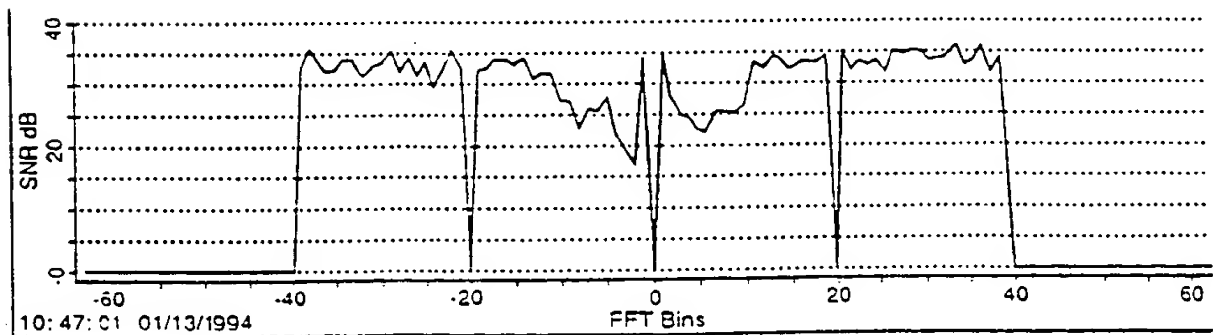
Fig. 6

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04L 27/06; H03D 1/00
US CL :375/340, 324; 370/69.1, 20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 375/340, 324, 216, 316, 322, 325, 260, 261; 370/69.1, 20, 19, 21, 121, 123; 455/142, 143,205

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	US, A, 5,499,271 (PLENGE ET AL) 12 March 1996, SEE FIGURES 1-2.	1-12
A	US, A, 5,278,826 (MURPHY ET AL) 11 January 1994, see abstract, col. 3, line 37 through col. 4, line 19.	1-12

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	
"E"	earlier document published on or after the international filing date	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"O"	document referring to an oral disclosure, use, exhibition or other means	
"P"	document published prior to the international filing date but later than the priority date claimed	"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 OCTOBER 1996	**19 NOV 1996**

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